Active and Sterile Neutrino Emission and SN1987A Pulsar Velocity

Leonard S Kisslinger, Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213
Sandip Pakvasa, Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822

Recently estimates have been made of the velocities of pulsars produced by the emission of sterile neutrinos during the first 10 seconds and by active neutrinos during the second 10 seconds after a supernova event reaches thermal equilibrium. Neutrinos produced with electrons in the lowest Landau level are emitted in the direction of the magnetic field, and the resulting pulsar velocity depends mainly on the temperature. Using measurements of the neutrino energies emitted from SN1987A, the temperature can be estimated, and from this we estimate the velocity of the resulting pulsar from both active and large mixing-angle sterile neutrinos.

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A supernova event, which is the gravitational collapse of a massive star, often leads to the formation of a rapidly rotating neutron star, a pulsar. It has been observed that many pulsars move with linear velocities of 1000 km/s or greater, the pulsar kick. See Ref.[1] for a review.

Electrons in very strong magnetic fields, such as those found at the surface of a protoneutron star created by a supernova, are in Landua levels [2, 3]. If the electron is in the lowest Landau level, n=0, it has only negative helicity with respect to the direction of the magnetic field, say in the z direction. This leads to neutrinos produced with the electrons by URCA or modified URCA processes to have momenta strongly correlated with the magnetic fields, which could produce pulsar kicks.

It was shown in a recent work on pular kicks[4] that if electrons created by the modified URCA processes, which dominate neutrino emission after 10 seconds[5], are in the n=0 level, only those moving in the z (B) direction will contribute to neutrino emision. Therefore, even though only one or two percent of the neutrino emissivity occurs during the period of approximately 10 to 20 seconds after the supernova collapse, since almost all emission is correlated in the z direction this can account for the observed large pulsar velocities, the pulsar kicks. The resulting pulsar velocity, v_{ns}, is proportional to the temperature, T, of the protoneutron star surface to the seventh power, and one must be able to estimate T in order to predict v_{ns}.

The largest neutrino emission after the supernova collapse takes place during the first 10 seconds, when the neutrinosphere starts at about 40 km, with the URCA process dominating neutrino production. However, due to the high opacity for standard model neutrinos in the dense region within the neutrinosphere, few neutrinos are emitted, and the large pulsar kick is not obtained[6]. This has led to studies of pulsar kicks coming from sterile neutrinos to which the active neutrinos oscillate. In a study using sterile neutrinos with a very small mixing angle and a large mass (mass > 1 kev), constrained to fit dark matter, it was shown[7] that large pulsar kicks can be obtained. More recently, using fits to the LSND[8] and MiniBoone[9] experimental data, which seem to need two large mixing-angle light sterile neutrinos[10, 11, 12, 13], it was shown[14] that these sterile neutrinos can also give rise to large pulsar velocities. As in Ref [4] for active neutrinos, it was shown that the pulsar velocity from large mixing angle sterile neutrinos is proportional to the temperature, T, of the protoneutron star surface to the seventh power.

In the present work we use the results of Refs [4, 14] to estimate the velocity of a pulsar produced by SN1987A. In the 10 second period in which the modified URCA process dominates neutrino emission, the radius of the neutrino sphere, R_ν, is a little smaller that the radius of the protoneutron star, R_{ns}, so all the created neutrinos correlated with the z direction are emitted. In ref[4] it was shown that with the probability of the electron being in the n=0 Landau level $\simeq 0.4$ and $R_\nu \simeq 9.96$ km, the velocity given to the neutron star during this period by active neutrinos, for a neutron star with the mass of our sun is

$$v_{ns}^{\rm active} \;=\; 1.03\times 10^{-4}(\frac{T}{10^{10}K})^7\frac{\rm km}{\rm s}\;. \qquad (1)$$

During the first 10 seconds, using the model of [11, 12] with two light large mixing angle neutrinos, it was shown that the velocity given to a pulsar is

$$v_{ns}^{\rm sterile} \;\simeq\; 3.35\times 10^{-7}(\frac{T}{10^{10}K})^7\frac{1}{sin^2(2\theta)}\frac{\rm km}{\rm s}\;, \qquad (2)$$

where the mixing angles of the two sterile neutrinos give $\sin^2(2\theta) = 0.004$ and 0.2

Clearly for a prediction of the velocity of the pulsar, one must know the temperaure at the surface of the protoneutron star quite accurately. If one knows the energy of the emitted neutrinos at 10 seconds, T is determined by the relationship that $kT = E_\nu/3.15$.

Twenty neutrinos from SN1987A were detected by Kamiokande-II[15] and IMB[16]. The energies of the neutrinos measured by IMB were two to three times larger than those of Kamiokande-II. This has been discussed in many papers. For the present work we need an analysis of the data to obtain a mean energy of the neutrinos at about 10 seconds. An early model [17] chose T=$4.1^{+1.0}_{-0.4}$. Since then there have been many analyses. See references [18, 19]. Although there are discrepancies, the general agreement is that the neutrino energy at 10 seconds is in the range 9-14 Mev, giving a temperature range:

$$T \simeq (3 \leftrightarrow 4.5) \text{ MeV} = (3.5 \leftrightarrow 5.2) \times 10^{10} K \;, \quad (3)$$

which results in our prediction from Eq.(1) that

$$v_{ns}^{\text{active,SN1987A}} \simeq (0.66 \rightarrow 10.6)\frac{\text{km}}{\text{s}} \;, \quad (4)$$

which is too small in comparison with other sources of pulsar kicks to be significant. Note that if the neutrino energy were 30 MeV, v_{ns} would be greater than 1000 km/s,for high-luminoscity pulsars.

From Eq(2) the velocity of the a pulsar produced via SN1987A by large mixing angle sterile neutrinos has the range given by T and $sin^2(2\theta)$

$$v_{ns}^{\text{sterile,SN1987A}} \simeq (1.08 \times 10^{-2} \rightarrow 8.6)\frac{\text{km}}{\text{s}} \;, \quad (5)$$

where we use the range $sin^2(2\theta) \simeq 0.004 \rightarrow 0.2$. Once more, we find that the resulting velocities are too small in comparison with other sources of pulsar kicks to be significant. Note also, if the pulsar momentum were to be produced by the emission of sterile neutrinos, although one one cannot detect sterile neutrinos and therefore determine the temperature, if there is a large mixing angle the sterile neutrinos can oscillate back to active neutrinos, which can be detected.

In conclusion, we find that the velocity of the pulsar from SN1987A resulting from the emission of either active or sterile neutrinos is too small to be significant.

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